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STATUS OF THE NATIONAL IGNITION FACILITY AND CONTROL SYSTEM*

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ABSTRACT

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is a stadium-sized facility under construction that will contain a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber with room for multiple experimental diagnostics. NIF will be the world's largest and most energetic laser experimental system, providing a scientific center to study inertial confinement fusion (ICF) and matter at extreme energy densities and pressures. NIF's laser beams are designed to compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. NIF is comprised of 24 independent bundles of 8 beams each using laser hardware that is modularized into line replaceable units such as optical assemblies, amplifiers, and multi-function sensor packages containing thousands of adjusting motors and diagnostic points. NIF is operated by the Integrated Computer Control System (ICCS) in an architecture partitioned by bundle and distributed among over 750 front-end processors and supervisory servers. Bundle control system partitions are replicated and commissioned by configuring the control database for each new bundle. NIF's automated control subsystems are built from a common object-oriented software framework based on CORBA distribution that deploys the software across the computer network and achieves interoperation between different languages and target architectures. ICCS software is approximately 80% complete with 1.1 million source lines of code delivered to the facility. NIF has successfully activated, commissioned and utilized the first four laser beams to conduct nearly 400 shots in 2003 and 2004, resulting in high quality data that could not be obtained on any other laser system. This presentation discusses NIF's early light commissioning, the status of the control system implementation and plans to complete installation of the remaining laser bundles on the path to fusion ignition.

INTRODUCTION

The National Ignition Facility (NIF) is presently under construction at the Lawrence Livermore National Laboratory (LLNL). NIF is a 192-beam laser system to study inertial confinement fusion (ICF) and the physics of extreme energy densities and pressures [1]. When completed in 2009, NIF will be able to produce 1.8 MJ, 500 TW of ultraviolet light for target experiments. This is sixty times as energetic as present laboratory capabilities. At this power and energy, NIF is expected to ignite deuterium-tritium plasmas in ICF targets. Presently the Project is approximately 80% complete with eight beams in the first bundle operational in the main laser bay. These eight beams have produced 150 kJ of 1.05-μm light (1ω) making it already the most energetic infrared laser.

Every NIF experimental shot is a complex computerized coordination of laser equipment and the efforts of system operators according to laser settings calculated by a physics model. The Integrated Computer Control System (ICCS) is a large-scale, automated system under development that provides reliable monitoring and control of 60,000 distributed control points comprised of electronic, optical, and mechanical devices, such as motorized mirrors and lenses, adaptive optics, energy and power sensors, video cameras, pulse power, and diagnostic instruments [2, 3]. The precise orchestration of these parts will result in the propagation of 192, nanosecond-long bursts of light along a 1-km path. The beams must arrive within 30-ps of each other at the center of a target chamber 10 meters in diameter, and they must strike within 50-μm of their assigned spot at a target measuring less than 1-cm long.

In 2003-2004, four beams were activated to the target chamber for target experiments in a campaign called NIF early light (NEL). One of the beams was also directed to a laser precision diagnostic station (PDS). On a beam line basis, NIF demonstrated operation at all Project completion criteria and long-term functional requirements and primary criteria. NIF also performed target experiments in four experimental campaigns. Experience gained operating NIF early in the Project construction both validated the control system architecture and more clearly exposed the next level of shot automation requirements to the software development team.

NIF PROJECT STATUS

The NIF facility layout is shown in Figure 1. The facility consists of two laser bays, four capacitor areas, two laser switchyards, the target area, and the building core containing the control room and master laser oscillator. In addition, there is an Optics Assembly Building and a Diagnostics Support Building. The laser is configured in four clusters of 48 beams, two in each laser bay. Each cluster has six sets of eight beams called a bundle that is the fundamental beam grouping in the laser bay. In the switchyard, each bundle is split into two sets of four beams, or quads, with one quad from each bundle directed toward the top of the chamber and the other quad directed toward the bottom. The irradiation geometry for an indirect-drive ICF ignition target focuses the upper and lower groups of 24 quads through the two laser entrance holes in the target hohlraum. Construction of the beampath and target area infrastructure is complete and installation of laser hardware and control systems is underway.

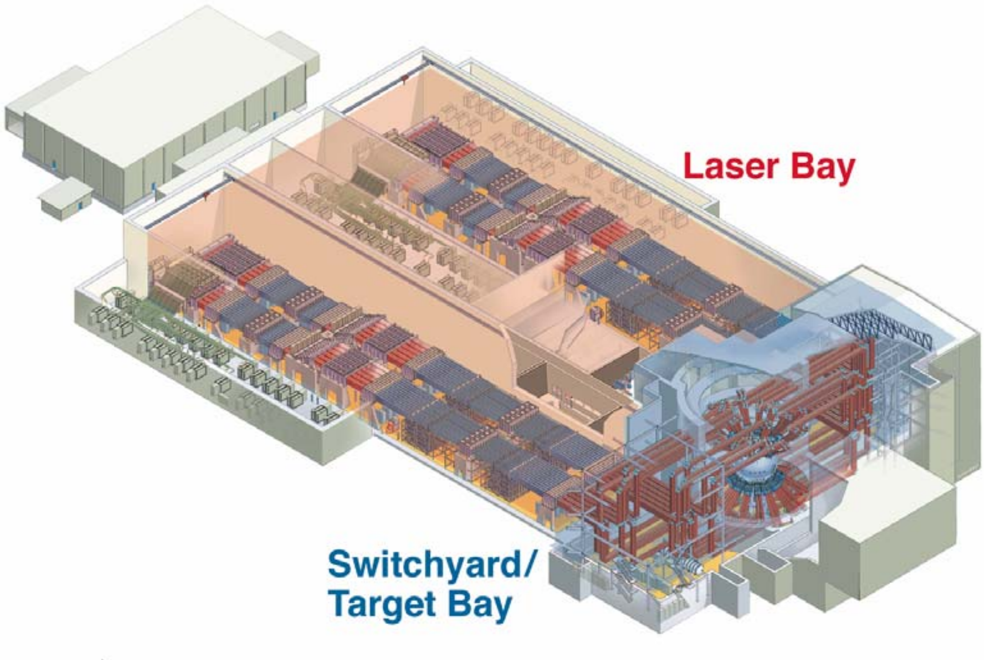

Figure 1. Layout of the National Ignition Facility.

A NIF laser beam begins with a 1-nJ infrared pulse from a master oscillator system that can provide a variety of flat to high-contrast pulse shapes. The pulse travels over fiber-optics to preamplifier modules (PAMs) for amplification and spatial beam shaping. Each of the 48 PAMs boosts the pulse to a maximum of 10-J. From the PAM the laser beam is split four-ways and enters the main laser system, which provides 99.9% of NIF's power and energy. Flashlamps that pump neodymium-doped glass slabs in the main amplifiers receive their power from the Power Conditioning System, which consists of the highest energy array (delivering up to ~400 MJ) of electrical capacitors ever assembled. An optical switch in each beam line called the plasma-electrode Pockels cell (PEPC) allows 4 passes through the main amplifier to increase the laser efficiency. After amplification the beam leaves the laser bay to travel through the switchyard, where it is redirected through the final optics assembly (FOA) and focused on target. A harmonic converter in the FOA converts the beam to the ultraviolet third harmonic (3ω).

All major laser components are assembled in clean, pre-aligned modules called line-replaceable units or LRUs. Numbering over 5,000, the LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filter assemblies, motors, and sensors that are designed to be robotically installed into NIF's beampath infrastructure, while maintaining the high level of cleanliness required for proper laser operation. Automated guided vehicles carry the pre-assembled LRUs within portable clean rooms that are docked with the corresponding beampath enclosure to effect installation.

In 2002, NIF began activating a quad of four beams to the target chamber for NEL experiments. Any one of the four activated NIF beams could also be directed to the separate PDS experimental area to fully characterize NIF's laser performance. The NEL experiments were used to demonstrate the performance of NIF design architecture and the operability of the facility. Over 400 shots were performed during the lifetime of NEL from January 2003 to October 2004. By the end of NEL operations, the facility could routinely perform two shots per operations shift.

Experiments were performed in the PDS to characterize the performance of a NIF beam. On a beam line basis, all Project completion criteria and long-term functional requirements and primary criteria were demonstrated. In separate PDS experiments, NIF produced 10.4 kJ of 3ω light and 11.4 kJ of 2ω light. This is equivalent to 2 MJ and 2.2 MJ, respectively, for 192 beams. The laser demonstrated its capability required for ignition.

The initial set of 13 target diagnostics to support laser performance characterization and target experiments have been commissioned. These included systems for imaging x-rays generated by laser irradiation of targets, for measuring laser light scattered from the target and for characterizing x-ray drive spectra within hohlraum targets. In addition, a velocity interferometer capable of measuring shock propagation and equation of state in materials at high pressure was commissioned. Experiments in laser-plasma interactions, laser propagation in plasmas, beam conditioning, hydrodynamic instabilities and hohlraum physics were performed.

INTEGRATED COMPUTER CONTROL SYSTEM STATUS

ICCS is a distributed, hierarchically organized control system that employs a scalable framework of reusable software to build uniform programs for beam control, injection laser, power conditioning, laser diagnostics, and target diagnostics [4]. The control system is comprised of two principle layers, supervisory controls overseeing front end processors (FEP) attached to the laser hardware. ICCS employs Ada95, Java, CORBA, and object-oriented techniques to enhance the openness of the architecture and portability of the software. Ada generally implements control system semantics. Java is used for the production of graphical user interfaces and the integration of commercial software, particularly the Oracle database system. CORBA provides transparent language binding and distribution middleware.

The physical partitioning of NIF's independent bundles has been extended to the control system computer architecture. Control processes and computers were reorganized by bundle to achieve better parallelism, to assure predictable scaling performance, and to reduce the impact of localized failures. This is referred to as "bundle-based partitioning" and had no impact on framework or supervisory software due to the location-independent features of the CORBA distribution architecture. Bundle independence greatly simplifies the control system software because each bundle is operated asynchronously from the others until the final countdown, at which point all systems are synchronized and fired by the master timing system. The impact to the hardware architecture was to increase the number of FEPs by a factor of two and the number of servers to 24 sets (i.e., equal to the number of bundles). The cost of this modification was limited by replacing the backplanes in certain large FEPs with three smaller backplanes and adding two more processor boards. This tactic avoided changes to the racks or cable plant. Larger planned servers were replaced with numerous inexpensive units. A large-scale, redundant Gigabit Ethernet network upgrade was also done to assure reliability, to isolate the bundles from each other, and to deliver predictable scaling performance in the network backbone. Over the next few years, computer systems and software that were fielded for the first bundle will be replicated, installed, and activated in the database to commission new bundles.

As a consequence of experience gained during NEL operations, over 300 sensor cameras in the beam control and laser diagnostics system were upgraded to high-resolution firewire cameras. A new PC-based FEP target architecture was added to leverage commercial code for firewire support. CORBA's language and processor transparency facilitated migration of the ICCS framework to Windows XP using an alternate Ada95 compiler technology (AdaCore GNAT Pro). The FEP can either capture shot data or deliver compressed streaming video to the operator consoles. The network-attached camera FEP is hosted on Pentium M processor blades (1 per camera).

The target diagnostics embedded control architecture was modified to use a single low-cost PC104 processor per device (e.g., a digitizer). The full diagnostic control is then composed within the supervisory software by aggregating the network-attached controllers. This approach simplifies the embedded software, improves reliability and provides easy re-use of devices in other diagnostics.

An automation framework was developed and deployed to automate bundle shots [5]. NIF's 4-hour shot sequence is comprised of shot lifecycle states that include reading shot goals from a physics model, aligning laser beams, setting laser parameters, configuring diagnostics, verifying critical status readiness, and conducting a final 4-minute countdown. The framework features a model-based workflow and provides scripted behaviours stored in the database that allow flexibility to modify automation instructions in the field without recompiling the software. The framework provides two major constructs to the application software: a workflow engine and a master state machine. The workflow engine organizes collaboration among subsystem supervisors and coordinates transitions between shot lifecycle states. The master state machine coordinates all bundle workflow engines. The automation framework will operate 24 bundles in parallel by coordinating processes distributed over 750 processors.

This new shot automation framework was deployed in April 2005 and used to perform main laser commissioning shots for the first bundle [Figure 2]. The software's flexibility was demonstrated for several different shot types including setup verification, high power, and amplifier tests. Recently a more efficient workflow model was deployed that achieved an improved shot cycle of 3 hours.

Figure 2. The NIF Shot Director oversees automated shot operations using ICCS.

Rigorous quality control processes established earlier in the Project continue to be effective at assuring ICCS software releases are successfully deployed [6]. A second test facility was constructed that shortened release delivery times by providing resources for integration in parallel with verification tests. The software inventory grew to 1.1M source lines of code (SLOC), which is comprised of 70% Ada and 30% Java. The code base is larger than initially estimated because new requirements were determined to include tool sets for supporting laser commissioning, diagnosing the distributed system *in situ*, and emulating devices for testing shot automation at scale in the test bed.

The ICCS team found the automated system to be more sensitive to software defects than were manual controls. This was especially evident in distribution failure modes. Quality metrics were analyzed to help determine appropriate corrective actions. The data indicated additional developer testing and code inspections should be used to augment intensive integration and verification testing practices already in place. Results obtained by increasing the early-phase quality controls resulted in substantially more defects being found when they are less costly to repair. Consequently, nearly 95% of all defects have been detected before ICCS is used in laser operations.

PLANS TO COMPLETE NIF

Presently, the NIF Project is approximately 80% completed. Almost all of the subsystem designs are completed. Over 5,700 LRUs need to be installed and commissioned. Completion of the Project involves primarily the assembly, installation, and commissioning of the LRUs and installing the supporting utilities and control systems. Factories for completing the final assembly of LRUs and control system electronics have been established on site to provide pre-assembled and configured units [Figure 3]. The Project is being completed in two phases. In the first phase, the LRUs are being installed and beam lines activated in the laser bays to the switchyard wall. Beginning in 2007, the Project will begin to build out the beam lines to the target chamber. Project completion is planned for March 2009. Presently, nearly 1000 LRUs have been installed, and one bundle of eight beams has been commissioned to the switchyard wall. During the activation, the bundle produced over 150 kJ of 1ω light. This is the highest energy pulse produced by a laser system at 4% of NIF's capacity.

Figure 3. On site electronics assembly facility will produce over 700 front end processors.

Manufacturing oversight and quality controls for these activities have been greatly enhanced to meet the challenges posed by such a large undertaking. Electronic enterprise resource management (ERP) tools and databases were developed by the Information Technology group to track NIF procurements, plan and report warehouse parts availability and shortages, and manage work orders for executing equipment assembly and installation. An integrated work permit process is in place to control all work performed on the site, which also assures that activities are performed safely and coordinated with other work in affected areas and/or subsystems.

A formal acceptance process is also being used during installation and commissioning. For example, control system elements are assembled and tested in the FEP factory, followed by installation qualification (IQ) in the facility during which the FEP is installed on the network, the database initialized, and the control cables checked out using the ICCS software, database, and test boxes in place of actual laser hardware. Later, LRUs are installed and attached to the control system cables. The commissioning team verifies correct operation of the control points in the LRUs with the control system. Finally, the assembled laser system is operationally qualified (OQ) using active systems and laser light. Each NIF bundle is only approved for operation after many IQ and OQ verification procedures are successfully completed and reviewed.

ICCS software will be extended by another estimated 300 KSLOC to add control for multiple bundles in 2006 and for clusters (6 bundles or 48 beams) in 2007. The final software development will increase automation support for the target chamber and experiments during 2008-2009, and ignition experiments beginning in 2010.

After the NIF Project is completed in 2009, the goal is to begin ignition experiments in 2010. Significant effort is required after the end of the Project to prepare for these experiments. The subsystems needed to begin the ignition experiments include additional diagnostics and a cryogenic target capability consisting of a target positioner, a cryogenic shroud, target installation glove box, deuterium-tritium ice layering and characterization station, and a transport system. The target will be cooled, filled, and layered next to the chamber and then inserted and aligned. An integrated plan called the National Ignition Campaign has been developed to meet this goal. The plan integrates a number of subsystems with the target physics and NIF operations into a multiyear effort culminating in the initial ignition experiments in 2010. The 2010 ignition experiments begin using laser energy of ~1 MJ with the energy ramping up to the full 1.8 MJ in 2011. A pre-ignition campaign is planned at the beginning of 2010 to study the energetics, symmetry, ablator performance, and shock timing to optimize target performance.

SUMMARY

The ICCS framework supports large-scale control systems and accommodates the complexities of distribution. The software architecture and CORBA middleware allow easy reconfiguration of the computer control system to isolate independent control segments and optimize performance. Design modifications to implement bundle-based controls alleviated concerns that the computer and software architecture could scale successfully as NIF was built out. Model-driven shot automation software has successfully reduced efforts required of system operators, achieved the required shot rate, and afforded operational flexibility to the Shot Director. The final 20% of software to be completed in the Project will extend shot automation to handle multiple bundles and the target systems.

The NIF Project is on schedule for completion in 2009. The remaining activities are primarily the replication, installation, and commissioning of LRUs, utilities, and bundle-based controls. One bundle of eight beams has been commissioned to the switchyard wall. NEL experiments have demonstrated that NIF will be able to perform as designed. User experiments with four beams have demonstrated the ability to operate as a facility. The experiments provided important data showing NIF’s value as an experimental facility as well as validating the control system design and clarifying automation requirements. Plans are in place to begin ignition experiments in 2010, the year after Project completion.

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